Feasibility of Reflectometry for Nondestructive Evaluation of Prestressed Concrete Anchors

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***Abstract*—Concrete dams and other large civil structures utilize steel cable anchors to improve strength and stability. Reflectometry methods that have been used for location of faults in electrical systems are examined as a possible method for location and quantization of possible deterioration on concrete anchors. This paper explores the feasibility of using electrical reflectometry methods for fault location on concrete anchors. Anchors must be electrically isolated from the surrounding structure, and the best results are obtained when tests can be made *in situ* over the lifespan of the anchor. Tests on 200 foot long anchors buried in wet sand confirm the possibility of using spectral time-domain reflectometry for location of full or perhaps partial anchor damage.**

***Index Terms*—Anchors, cable, reflectometry.**

I. Introduction

ANCHORS for prestressed concrete (metal-tensioned systems) are used for construction and repair of foundations, retaining walls, and excavated and natural soil and rock slopes. This paper discusses a new method for testing anchors that are made of several steel cables. At least one end of the cables is held together by a trumpet-shaped head. The other end may have a similar anchor head, or may be grouted into the cement foundation. The anchor may be grouted (surrounded by cement) or ungrouted. Once installed, metal-tensioned systems are vulnerable to failure by corrosion of the metal elements, loss of anchorage, or both, but visual observations of the conditions at the element head assembly often do not indicate actual or potential problems, and cases of premature failure have already been documented [1]. The most common method for evaluating the integrity of ungrouted anchors is the liftoff test which places a large strain on the cable (often using a crane) to see if the anchor remains intact. This method is expensive and difficult and may result in needless damage to the cable. It can also not be done for grouted anchors. Electrochemical tests (measurement of half-cell potential and polarization current) can be used to detect corrosion but do not give information on how much of the cable is corroded. Acoustic wave propagation methods such as impact (hammer) and ultrasound techniques have also been tested. For shorter anchors (10–20 feet), these may be useful. Attenuation and dispersion limit their use on longer cables. Electrical reflectometry has been tested in the past. Time-domain reflectometry (TDR) sends a step or pulse of voltage down the cable, where it reflects from the open end. The time delay of the reflection tells the distance to the end of the cable. This method is subject to attenuation and dispersion, just as the acoustic wave methods are. This method requires two electrical paths… a positive path (the anchor) and a ground wire nearby. Typically, this ground wire needs to be run in parallel with the anchor, generally precluding its application in practice. This paper describes a new method—spectral time-domain reflectometry (STDR) where a digital code is used for electrical reflectometry. This system has previously been applied to location of faults on electrical wires in aircraft [5]. This system uses correlation on the reflected digital code to determine the distance to the end of the wire. If the code is made long enough and the correlation is done over a "long" period of time (seconds as opposed to milliseconds), the signal-to-noise ratio can be made large enough to extract even a very highly attenuated signal. Reflectometry and STDR, in particular, is described later in this section. The theory behind using electrical reflectometry for testing of anchors is described in Section II. The feasibility of this method is evaluated in Section III by testing anchors of known length in horizontal trenches. Section IV concludes that the STDR method holds promise for location of faults on grouted and ungrouted anchors.

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A. Basic Reflectometry

Reflectometry methods are among the most commonly used methods for testing wires. A high-frequency electrical signal is sent down the wire, where it reflects from any impedance discontinuity. The reflection coefficient gives a measure of how much signal is returned and is given by

$$\Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} = \frac{Z_L - Z_o}{Z_o + Z_L} \tag{1}$$

where Z_o is the characteristic impedance of the transmission line, and Z_L is the impedance of the discontinuity [4]. For instance, the reflection coefficient for an open circuit (Z_L = infinity) is 1, and the reflection coefficient for a short circuit ($Z_L = 0$) is -1. The characteristic impedance of anchors in concrete is typically around $Z_o = 75$–300 ohms.

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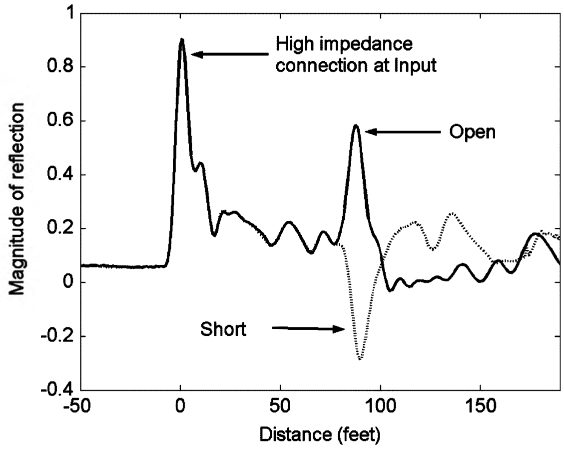

Fig. 1. STDR responses for an 80 foot wire (paired single 22 gauge wires bundled with other wires) that is short or open circuited on the end.

The time or phase delay between the incident and reflected signals tells the distance to the fault, and the observed magnitude of the reflection coefficient tells what the impedance of the discontinuity is. Fig. 1 shows the STDR responses for an 80 foot wire that is short or open circuited on the end. The first peak shows where the reflectometer is connected to the wire, and the second peak shows the end of the wire. The height and polarity (positive, negative) of the reflected peak gives the reflection coefficient. In reality, the raw data is actually given as a time delay rather than distance. The distance L is the velocity of propagation multiplied by the time delay. The velocity of propagation used in these tests is 0.562 times the speed of light. This velocity will depend on the size of the conductors, their separation, and what is between them (concrete, metal structure, etc.). Hard faults (open and short circuits) have been located with STDR to within 3–5 inches on controlled impedance cables and 6–8 inches on uncontrolled impedance cables in air. This paper evaluates how accurately they can be located in concrete.

Reflection coefficients greater than 10% are relatively easy to identify and locate just by looking at the reflectometry response by eye. Impedance differences below 10% become progressively more difficult to identify, as their response is much smaller, and eventually the peaks from the reflection are so small they cannot be visibly seen. The reflections from long dam anchors are very small because of the attenuation of the signal in the concrete surrounding the anchors. The reflectometry response in Fig. 1 is for a wire in air with minimal attenuation. For anchors in concrete, this peak is virtually invisible.

The challenge of using reflectometry for detection of damage on prestressed concrete anchors is to locate reflections that are smaller than can be visibly seen on the signal trace. In order to identify and locate these very small reflections, a test system with a very high signal to noise ratio is used to measure the reflections. Then signal processing that compares a baseline test signal to a later comparison test signal is used to identify and locate changes in the reflected signals that indicate the location of the fault. Increasing the signal to noise ratio can be done in many ways, including increasing the amount of test time that is averaged to give the final values. (For tests shown here, the default integration time was 2 s.) Another challenge with locating small reflections is that changes in the environment surrounding the cable may also create small reflections that are of no interest. This challenge is commonly overcome by using a baseline (initial test) of the system of interest. Subsequent tests are then compared to this baseline (subtracted from the baseline) in order to locate changes of interest. This works very well for objects that do not move (such as dams), but does not work as well for objects that move and vibrate (such as aircraft) [7]. A baseline is used in all of the tests in this paper. Another potential source of error in reflectometry methods is a "blind spot" that occurs on wires that are very short. When locating a fault far from the tester, the peaks are well separated and easy to distinguish and measure. When the fault is closer to the tester, the peaks overlap and are harder to distinguish. It is clear that a fault has occurred, and that it is close to the near end of the tester, but the accuracy to which this location can be predicted is compromised. This can be resolved very well in the case of dams by using an extension cable between the tester and the dam wire (as was done in these tests), so that the blind spot is in the extension cable rather than the dam anchor.

B. Spectral Time-Domain Reflectometry (STDR)

There are many different reflectometry methods, each of which is distinctive in signal that is sent down the wire under test and the method of detecting the time delay of that signal. In this project, STDR [5], [6] was used because of its ability to increase the sensitivity of the tester by increasing integration time. Spread-spectrum methods have been used extensively in communication systems, where a pseudonoise (PN) code is used to code the data for wireless transmission. This basic concept can be applied with excellent precision to fault location on aging wiring. It is currently used commercially for location of faults on direct subscriber lines (DSLs-a form of internet) lines [8] and for location of faults on overland power distribution lines [9]. Spread-spectrum methods have been shown to be an effective method for locating hard and soft faults on aircraft wiring with precisions on the order of a few inches [5], [6]. In order to achieve this resolution, the correlation is done in hardware as described next.

There are two types of spread-spectrum methods. Spectral time-domain reflectometry (STDR) uses a PN code as the test signal. Spread-spectrum time-domain reflectometry (SSTDR) uses a sine wave modulated PN code as the test signal. A PN code is a digital code, many bits long, that appears to be a random (noisy) combination of 1's (positive voltages) and 0's (negative voltages). This code is not actually random, however, and is easily reproduced. This code is a traditional signal used for cell phones and is generated with a series of JK flip-flops. These codes have very high self correlation and very low correlation with other codes or with delayed versions of themselves and, therefore, end up being ideal test signals for reflectometry methods. STDR is more applicable to the present application, because it has more of its power in the low-frequency range and, therefore, propagates further in lossy environments. A lossy environment such as anchors imbedded in concrete has some nonzero electrical conductivity, which creates loss (attenuation) in a signal passing through this environment. Power is converted to heat in these lossy environments.

The basic STDR/SSTDR system is shown in Fig. 2. The maximum length (ML) PN code (up to 1024 bits) running 6–12-or-24 Mbits/s is generated using a series of tapped

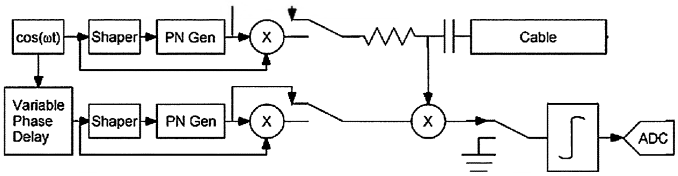

Fig. 2. Circuit diagram for STDR/SSTDR system.

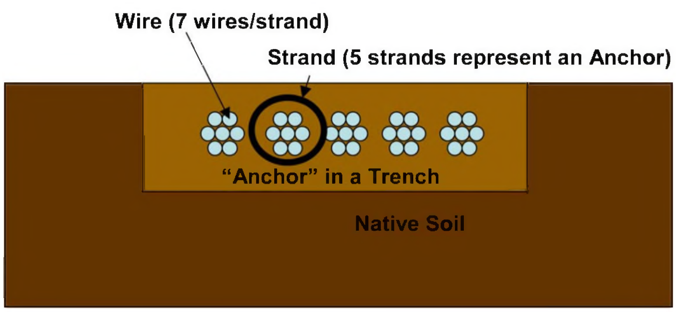

Fig. 3. Cross section of simulated anchor for this test. Another identical anchor in another trench a few feet away was used as the “ground” reference.

flip-flops. A multiply and integrate circuit is used to perform the correlation in hardware, and an analog phase shifter is used to shift the original PN code to find the correlation for every very small phase (time) delay and create the equivalent of a standard time-domain reflectometer (TDR) trace. The STDR test equipment used for these measurements has a PN code that is 254 bits long at 6 MHz. Higher frequency tests did not work as well. Data was integrated for 2 s. Data is stored on a handheld computer and downloaded to a regular PC for analysis and plotting for these tests, although in practical application the baseline is stored on the handheld, and all analysis is done there.

II. Testing Concrete Anchors With Reflectometry

A simplified test layout was used for these sand tests in order to facilitate building a test system that we could easily access in order to deliberately damage anchors in a controlled fashion. The tension (or lack of tension) on the anchors is not a factor in this test. The impedance, velocity of propagation, etc., are not changed by the tension. Fig. 3 shows the cross section of a simulated anchor used for the sand tests described in this paper and the definitions of wire, strand, and anchor. It is important to note that the anchors must be electrically isolated from the surrounding metal in the dams. This depends on the construction method by which they were installed. If the anchor heads are connected into the rest of the rebar in the dam, then an isolating material is needed between the anchor head and its support.

A. *Impedance of Concrete Anchors*

These “sand tests” use dirt and sand as a substitute (electrically) for concrete. The relative permittivity (dielectric constant) of the materials controls the electric fields which, in turn, determine the characteristic impedance of the anchors. Wave propagation on an anchor depends on the attenuation properties of the material (concrete/dirt) and the anchor material (steel). The

TABLE I
Electrical Properties of Concrete and Related Anchor Materials [3]

Material	ε_r	σ (mS/m)
Dry concrete (outdoors)	4-10	4
Dry concrete (outdoors)	4-10	20
Dry concrete (oven-dry)	4-10	$1\text{x}10^{-3}$
Wet concrete (uncured)	10-20	
Grouting	4	unknown
Plastics	2-4	approx. 0

TABLE II
Measured Soil Bulk Conductivity and Water Content at Test Site

Test Points	Bulk Electrical Conductivity σ (mS/m)	Water Content (multiply by 100 for %)
Wet sand		
1	1.6	0.071
2	1.7	0.063
3	4.6	0.098
4	1.8	0.08
5	1.7	0.074
Wet Native (clay) soil		
1	34.8	0.095
2	21.9	0.157
3	22.9	0.203
4	26.5	0.23
5	25.5	0.242
6	38.2	0.237

main factors controlling these properties are the resistivity or conductivity of the material, which are given in Table I. Cured concrete with different moisture levels are also given in [1].

Table II shows the impedance of dry and wet sand at the test site. This was measured using a TDR-100 time-domain reflectometer from Campbell Scientific with a moisture measurement probe, a commercially available instrument.

B. *Impedance of Steel Anchors in Concrete*

The characteristic impedance (Z_o), velocity of propagation (vp), and attenuation of any two parallel cables in concrete can be found from the RLGC model of transmission lines, often called the lumped element transmission line model [4]. This model is shown in Fig. 4. The “lumped” elements represent different electrical aspects of the transmission line.

R′: Combined resistance of both conductors/unit length (ohm/meter).

L′: Combined inductance of both conductors/unit length (H/m).

G′: Combined conductance of both conductors/unit length [S/m $= 1/$(ohm-meter)].

C′: Combined capacitance of both conductors/unit length (F/m).

Two parallel anchors in concrete can be represented as a two-wire line, whose cross section is shown in Fig. 5. A two-wire line is simply when two wires of radius “a” are separated by a

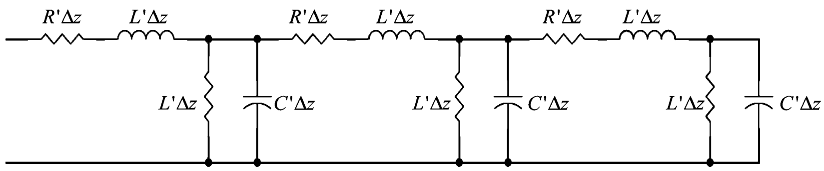

Fig. 4. Lumped element (RLGC) model of a transmission line.

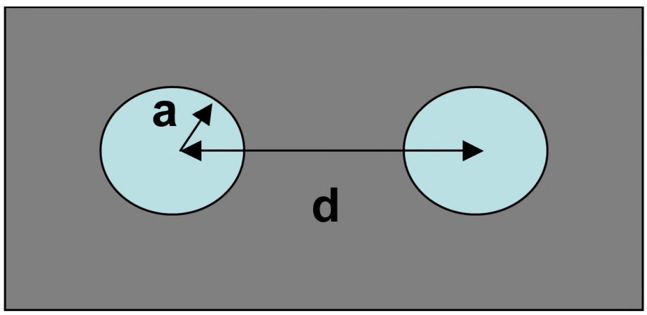

Fig. 5. Cross-sectional geometry of a two-wire line.

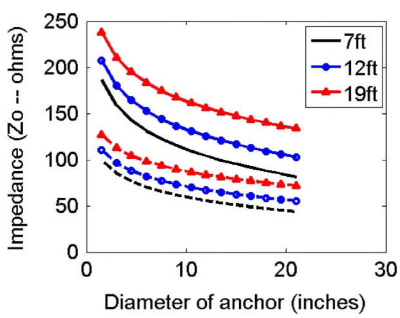

Fig. 6. Impedance (Z_o) of steel anchors in wet concrete/dirt ($\varepsilon_r = 4, \sigma = 2$ mS/m) as a function of radius of the anchor and trench spacing. The real part of the impedance is shown in the solid lines, and the imaginary part is shown in the dashed lines.

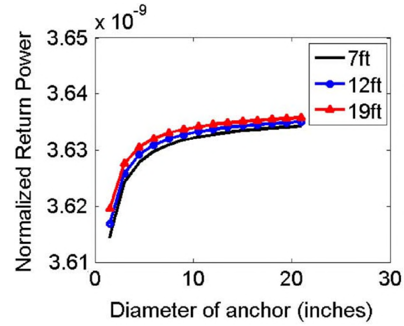

Fig. 7. Normalized return power of steel anchors in wet concrete/sand ($\varepsilon_r = 4, \sigma = 2$ mS/m) as a function of radius of the anchor and trench spacing at 6 MHz.

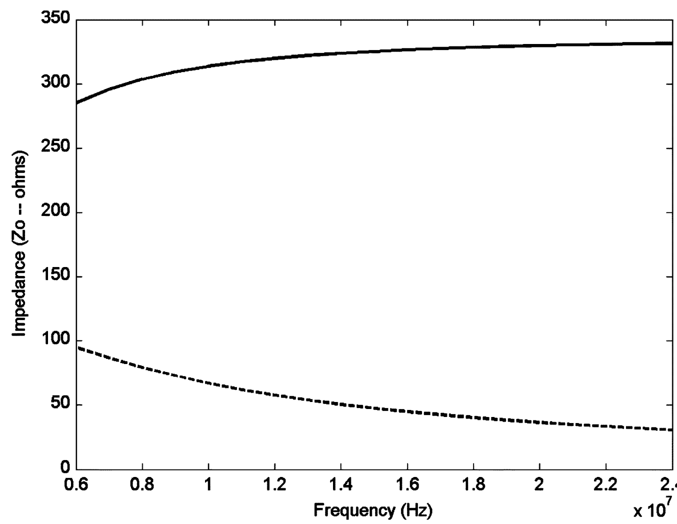

Fig. 8. Impedance (Z_o) of steel anchors as a function of frequency. The electrical properties of concrete/dirt are $\varepsilon_r = 4$ and $\sigma = 1$ mS/m. The anchor is a $5/8''$ diameter steel anchor with a trench spacing of $7'$. The real part of the impedance is shown in the solid lines, and the imaginary part is shown in the dashed lines.

distance "d." The material surrounding the lines (in this case, dirt, shown in gray) is a lossy dielectric.

The RLGC parameters and their associated impedance, velocity, and loss factors can be calculated using the equations. The impedance Z_o determines the ratio of voltage to current on a transmission line. Even though it has the units of ohms, it does not represent resistance, only the ratio of voltage and current. The impedance can be complex if loss is present, meaning that the voltage and current can be out of phase with each other. This simplified formula does not take loss into account and is, therefore, strictly real. Fig. 6 gives the impedance (Z_o) of steel anchors in wet (12% moisture) concrete/dirt ($\varepsilon_r = 4, \sigma = 20$ mS/m) as a function of radius of the anchor and trench spacing. The velocity of propagation is 0.4216–0.4217 times the speed of light for all of the configurations given here. Fig. 7 gives the returned signal (indicative of attenuation) for this configuration. The trench spacing and anchor radius have minimal effect on the impedance and velocity of propagation for typical radii of dam anchors.

The properties of the concrete/soil surrounding the anchors have a significant effect on the attenuation, and a lesser effect on the characteristic impedance (Z_o) and velocity of propagation (vop). The extremely strong attenuation is a cause for concern for any testing, as this indicates the power that returns to the reflectometry test unit. The unit must be able to receive and process this signal. The measured values of conductivity of the soil used in these tests are sufficiently high that the tests done here are strongly representative of expected values in concrete. The expected return signals are EXTREMELY low, hence the need for great sensitivity.

The frequency also plays a major role in all of the parameters listed above (Z_o, vop, attenuation), as shown in Figs. 8–10. The STDR signal has a broad range of frequencies, as shown in Fig. 11. Each individual frequency is attenuated according to

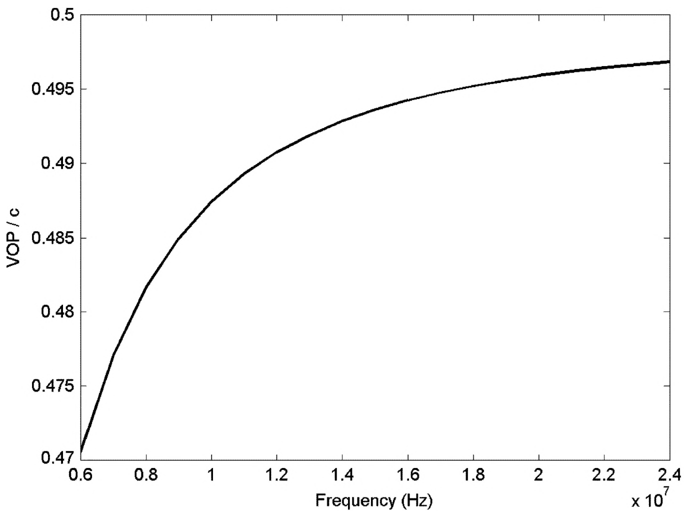

Fig. 9. Velocity of propagation (vop) of steel anchors as a function of frequency. The electrical properties of concrete/dirt are $\varepsilon_r = 4$ and $\sigma = 1$ mS/m. The anchor is a $5/8''$ diameter steel anchor with a trench spacing of $7'$.

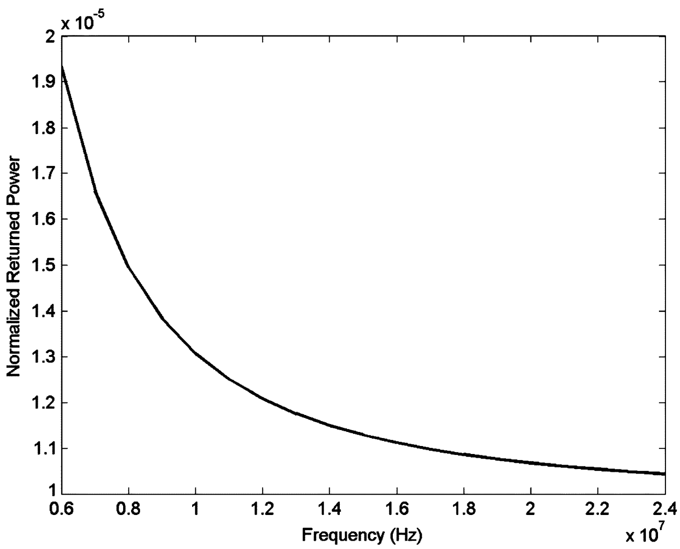

Fig. 10. Attenuation of steel anchors as a function of frequency. The electrical properties of concrete/dirt are $\varepsilon_r = 4$ and $\sigma = 1$ mS/m. The anchor is a $5/8''$ diameter steel anchor with a trench spacing of $7'$.

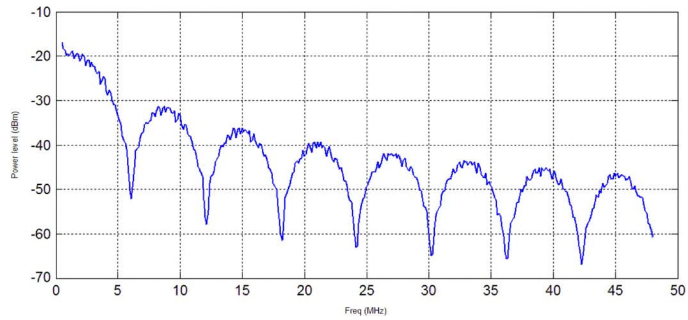

Fig. 11. Frequency spectrum of the 6 MHz STDR signals.

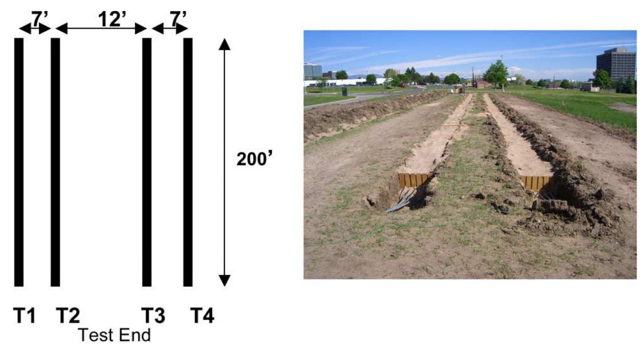

Fig. 12. Four parallel trenches were used simulate anchors in concrete.

Fig. 13. (Left picture) Ends of two anchors extending from trenches 1 (left) and 2 (right), $7'$ apart. This shows the plywood spacers used to hold the strands approximately $4''$ apart in the trenches, as shown in the right photo.

Fig. 10. It is clear that higher frequencies are not helpful in these tests.

III. Test Setup

A. Test Bed

A test bed was created at the Bureau of Reclamation in Denver, Colorado under the direction of Dr. Bill Kepler. The test bed consisted of four parallel $200'$ trenches (each $2'$ wide and $2'$ deep), as shown in Fig. 12. Each trench was filled with $1'$ of sand, and then five strands of $5/8''$ 7-wire cable (the same type as used in Mactaquac Dam) were placed in parallel. Each strand was held apart by a plywood spacer to ensure that they did not touch along the length of the anchor (this was a problem with the original concrete beam tested at the Bureau of Reclamation in 2006), as shown in Fig. 13.

B. Connection of Dam Anchor Test Unit (DATU) to Simulated Anchors

In order to simulate the normal configuration where multiple strands are short circuited together at the anchor head to create a single anchor, the five strands in each trench were tightly held together with duct tape, as shown in Fig. 13 (left picture). The Dam Anchor Test Unit (DATU) was connected to the simulated anchors with approximately 10–$20'$ of 12 gauge copper wire (available from typical home improvement centers), depending on the distance to each trench being tested. A metal pipe clamp was used to connect the 12 gauge wire to the bundle of strands representing the anchor, as shown in Fig. 13. In order to speed up collection of test data from multiple trenches, wires were run to each trench, and then connected individually to the DATU, connecting and disconnecting sequentially during each data collection. Fig. 14 shows the connection of the DATU to the simulated anchors in trenches 3 and 4. Care was taken to minimize the coils or loops in the 12 gauge (green) connection wires. (Left photo) Twelve gauge wires were connected to the 90 ohm coaxial cable

Fig. 14. Connection of DATU to simulated anchors in trenches 3 and 4. Care was taken to minimize the coils or loops in the 12 gauge (green) connection wires. (Left photo) Twelve gauge wires were connected to the 90 ohm coaxial cable using a banana-to-BNC connector as shown in the right photo. Testing on subsequent days was made easier (on our fingers!) by soldering banana plugs to the 12 gauge wires, so they could be simply plugged into the banana jacks.

(a) (b)

Fig. 15. Simulated damage. (a) Shows five strands completely cut and pulled away from each other. (b) Shows strands that were cut and not pulled away from each other. Both fault types gave similar results.

using a banana-to-BNC connector as shown in the right photo. Testing on subsequent days was made easier (on our fingers!) by soldering banana plugs to the 12 gauge wires, so they could be simply plugged into the banana jacks.

C. Simulated Damage

Damage to the anchors was simulated by cutting them with an oxygen acetylene torch. An example of these cuts are shown in Fig. 15. Fig. 15(a) shows five strands completely cut and pulled away from each other. Fig. 15(b) shows strands that were cut and not pulled away from each other. Pull tests (described later) were done to determine the spacing in Fig. 15(b) that was detectable.

D. Test Results

For each test, an initial test (baseline) was taken when the wires were 200 feet long. This baseline, which is different for each trench, was used as the baseline for all future tests of that trench, unless specifically noted in the report. An example baseline is shown in Fig. 16. Similar baselines were collected for each trench spacing ($7'$, $12'$, $19'$ and $26'$). The large peaks at the front are from the connection of the test unit to the cable. The signal is quickly attenuated by the cable, and the end of the cable cannot be visibly seen from this data. Data from subsequent tests will then be subtracted from this baseline in order to locate the end of the cable or a break/damage along its length.

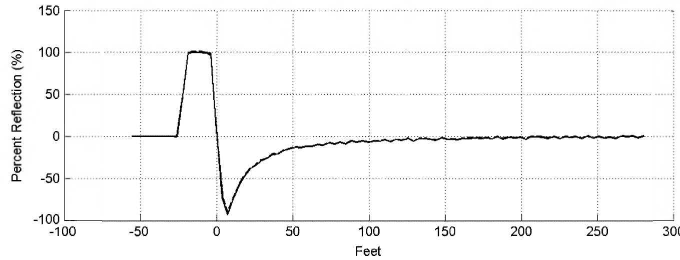

Fig. 16. Example baseline collected from two $200'$ wires 7 feet apart.

In practice, this baseline represents the sampled data that a dam operator would have taken when the dam was new (this is optimal), or partially aged (which should still be functional). Any change from this baseline represents a change in the impedance of the anchor being measured and indicates a break or possible damage. Because of the highly lossy nature of the soil (or concrete) surrounding these anchors, the reflectometry peak that would normally be used to locate the end of the cable was not readily visible beyond a few feet. Thus, it was only possible to locate breaks on cables up to about $10'$ away just by examining the response (not using a baseline). Breaks beyond this distance required use of a baseline taken before the damage occurred. Also, we attempted to use one trench as a baseline for another but found that this was not functional. There was more change between trenches than from the small changes we were seeking. Thus, the only functional method for locating breaks that were more than $10'$ from the test end was to use a baseline approach that would require *in situ* sensors testing at continuous intervals over time. Location of a break in the anchor was done by testing the wires when they were all $200'$ long (collecting this data as a baseline), cutting one of the anchors (all five strands, in this case), retesting, and subtracting the new test data from the original baseline. The differences for several break locations are shown in Fig. 17 for anchors $7'$ apart. For anchors that are $12'$, $19'$, and $26'$ apart, the peaks are progressively smaller and the noise larger. Based on these tests using a baseline, a complete break in the cable can be seen for anchors that are $7'$, $12'$, and $19'$ apart up to 160 feet and 26 feet apart up to about $140'$. Breaks further away than these MAY be detectable with future improvements, but it is not reasonable to expect conclusive results on them with the current hardware.

In order to simulate a partially corroded (or partially broken) anchor, each of the five strands were cut one at a time and pulled physically apart from the other parts of the cable so there was no possibility of electromagnetic coupling to the other parts of the cable. Smaller breaks were also tested, and found to be virtually identical to those that were pulled well apart. Partially damaged anchors showing effect of cutting 1,2,3,4, or 5 strands are shown in Fig. 18 for anchors $7'$ apart. For cuts up to $160'$ it appears that partial damage to the anchor can be identified. As for anchors

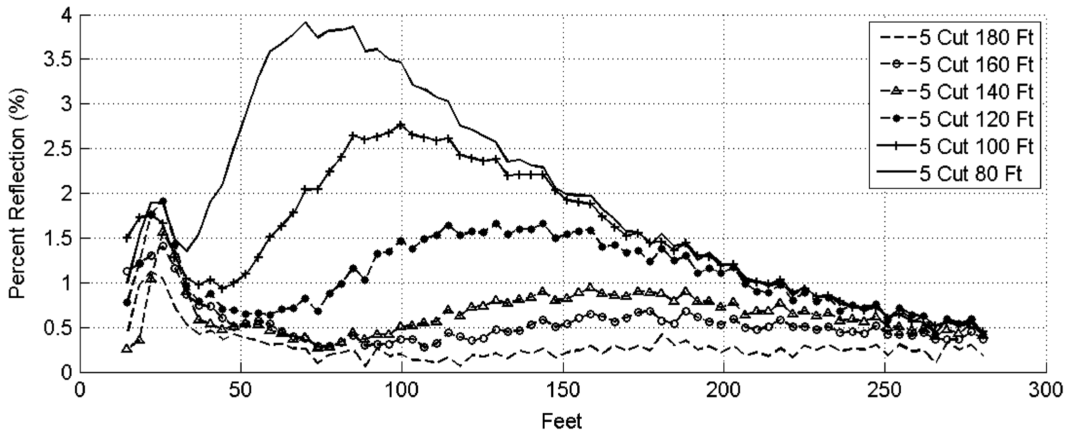

Fig. 17. Location of breaks in anchors that are separated by 7 ′.

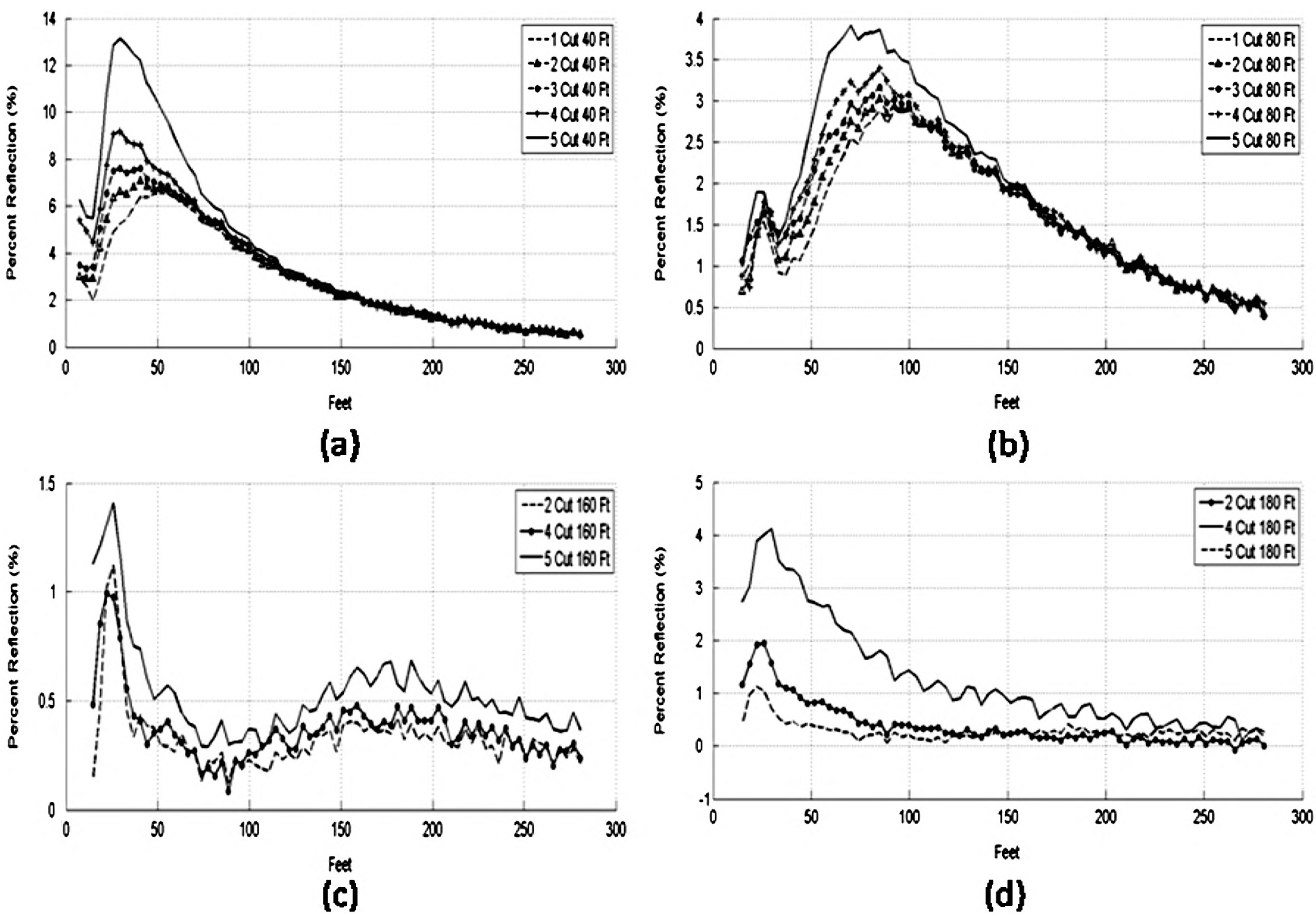

Fig. 18. Partially damaged anchors showing effect of cutting 1, 2, 3, 4, or 5 strands. (a) Cuts at 40 ′. (b) Cuts at 80 ′. (c) Cuts at 160 ′. (d) Cuts at 180 ′. All data is compared to a baseline at 200 ′. All anchors are in trenches 7 ′ apart. For cuts up to 160 ′ it appears that partial damage to the anchor can be identified.

that are fully cut, increasing the separation between anchors reduces the sensitivity of the method. It should also be noted that the strands in these tests were separated by wooden spacers, representing the configuration where multiple strands are separated in space. Other types of anchors have all of the strands touching or bundled together. These types of anchors were found to have reflectometry responses that were significantly less sensitive to partial damage.

IV. Conclusion

In conclusion, it appears from these tests that it is feasible to use STDR to find damaged structural anchors. The 6 MHz STDR tester was able to locate breaks in the anchors up to 160′ away, when comparing the cut anchors to a baseline measurement (see Table III for actual distance results). In all measurements, the signal is quickly attenuated, and in the baseline tests the end of the anchor (200 feet away) cannot be visibly detected

TABLE III
DETECTABLE FAULT DISTANCES FOR 6 MHz STDR TESTER

Trench spacing (feet)	Number of Cut Strands	Detectable distance limit of (feet)
7'	1	Not detectable
	2	140'
	3	140'
	4	140'
	5	160'
12'	1	120'
	2	120'
	3	120'
	4	120'
	5	160'
19'	1	Not detectable
	2	120'
	3	120'
	4	140'
	5	160'
26'	1	Not detectable
	2	120'
	3	120'
	4	120'
	5	140'

All cuts were made with a torch.
No cut was made with a 12' spacing at 140' so some of the individual cuts may be able to be detected at longer lengths.

from the data. With the equipment used, the greatest distance at which damage could be detected by subtracting test data from baseline data was 120–160 feet. Partial damage could be detected in many of these cases. The baseline needed to be from the same trench with as near the same connection as possible. Without using a baseline, breaks could only be detected if they were within approximately the first 10 feet of the anchor.

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